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THE INFLUENCE OF LOCAL WINDS ON FALLOUT

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By

JAMES D. KANGOS — JOSEPH P. GERRITY, JR.

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THE TRAVELERS RESEARCH CENTER, INC.
250 CONSTITUTION PLAZA, HARTFORD, CONNECTICUT 06103

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Prepared by
James D. Kangos
and
Joseph P. Gerrity, Jr.

7464-164

THE TRAVELERS RESEARCH CENTER, INC.
250 Constitution Plaza Hartford, Connecticut 06103

for

U.S. ARMY ELECTRONICS COMMAND, Fort Monmouth, N. J.

PURPOSE

The purpose of the study is to formulate existing information on the structure of local wind systems and local (close-in) fallout characteristics into a computerized computational model for use in estimating the influence of local wind circulations on the deposition of close-in fallout.

ABSTRACT

Information on the structure of the sea breeze obtained by previous observational and theoretical studies has been employed to formulate a kinematic model of the wind field associated with the sea breeze. Existing information on the structure of the stabilized fallout cloud has been compiled for use in the numerical computation of the deposition of the cloud particles through specified local wind fields.

A program was constructed for the numerical computation of fallout transport through an analytically prescribed two-dimensional local wind circulation and for the computation of its ground deposition pattern. The computer program was used to evaluate the fallout deposition pattern from simple models of the stabilized cloud through alternative models of the sea-breeze wind fields.

The planned development of a three-dimensional kinematic model of the sea-breeze wind field and of a computer program for the computation of fallout transport through it, is discussed.

PUBLICATIONS, LECTURES REPORTS, AND CONFERENCES

On April 8, 1965, Mr. Gerrity, at the invitation of Mr. Conover, attended a planning conference on work on an Improved Land Fallout Model held at Technical Operations, Inc., Burlington, Mass.

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1.0 INTRODUCTION

The occurrence of a nuclear detonation, either in the air or under the surface, with subsequent venting, introduces into the atmosphere material which has been rendered radioactive. This material is distributed through the atmosphere in the immediate proximity of the detonation by the convective circulation induced through the heating of the air by the energy released in the detonation. The extent of the penetration of the radioactive material through the atmosphere is dependent upon the energy yield of the detonation, the structure of the atmosphere, the nature of the material rendered radioactive, and the altitude at which the detonation occurred. During the time period required for the detonation-induced convection to subside, complex thermodynamic and radiochemical processes are active within the mixture of air and radioactive materials. The net result of this period of radioactive cloud growth is the distribution of the particulate, radioactive material throughout the region occupied by the cloud.

In the past, simplified models of this final cloud distribution of radioactive material have been employed to specify the initial data for the subsequent computation of the redistribution and ultimate deposition of the particulate matter upon the earth's surface. At the present time, considerable effort is being expended to improve our knowledge of the mechanisms relating certain of the factors controlling the cloud growth to the characteristics of the final stage in the process (widely referred to as the "stabilized fallout cloud").

In view of the effort to improve our current capability to specify the "source cloud" characteristics, it is considered timely to improve that phase of the fallout computation which transforms the "source cloud" data into subsequent deposition patterns or transit dose-rate records. One aspect of this transport problem which has received only very limited consideration thus far is the influence of the so-called "local atmospheric circulations".

The work being reported in this paper is an extension of the preliminary investigations of the significance of local circulations [5, 6] carried out at The Travelers Research Center, Inc. (TRC), under contract with the U.S. Army Electronics Laboratory.

This earlier work led to certain conclusions which we will now briefly summarize;

(a) Two-dimensional, vertical circulations which do not change during the time required for deposition of a fallout cloud can alter the time of deposition but not the final pattern of deposition.

(b) When such circulations intensify or diminish during the time required for deposition, the onset-time, duration, and final pattern of fallout deposition can be modified.

(c) Two-dimensional, horizontal circulations affect the horizontal pattern, but not the time of deposition. Vertical air currents must exist if the time of deposition is to be modified.

(d) Three-dimensional circulations, even when temporally steady, influence both the time and pattern of deposition.

(e) The compressibility of the atmosphere is only significant when the speed of the vertical air currents is comparable to the fall speed of the fallout particles.

(f) The influence of the two-dimensional, temporally-varying, vertical circulation on the time and pattern of deposition was found to decrease by an order of magnitude as the fallout particle fall speed varied from 25 cm sec^{-1} to 1 m sec^{-1}. In the case of the slower falling particles, significant changes (of the order of 100%) in the deposition pattern and time of deposition (several hours) were computed over limited regions.

(g) The potential significance of the local circulation on the pattern and time of deposition depends predominantly on the time and position of the nuclear detonation in relation to the temporal phase in the life-cycle of the local circulation.

The technical objectives of the current program are:

(a) to automate the procedures for computing fallout trajectories employed in the past effort, and to extend the method so that general three-dimensional wind circulations may be accommodated; and

(b) to improve upon the realism of the two-dimensional kinematic model of the sea-breeze circulation utilized in the previous work; to extend the scope of the wind models treated to include three-dimensional sea-breeze circulations with over-riding synoptic-scale flow patterns, and to formulate kinematic models of the mountain-valley wind field.

In this progress report, we will present the automated two-dimensional sea-breeze model and fallout computation programs. The results of a limited number of numerical computations are also presented and discussed. We have also included discussions of the three-dimensional fallout computation logic as well as the three-dimensional sea-breeze models which have been formulated for subsequent use. In Appendix B, we present the computer program which has been developed for computing the deposition of fallout passing through a two-dimensional local circulation.

2.0 THE SEA BREEZE

2.1 Review of Literature

Up to the late 1950's, observations of the sea breeze were confined to vertical soundings of the horizontal wind components at a single geographic location, and to routine surface observations of meteorological elements. A brief summary of these observations based on an article by Defant [2] follows.

When the prevailing large-scale flow is light, the sea breeze develops as a small circulation in the immediate vicinity of the coast. The circulation then gradually increases in depth and horizontal extent, both landward and seaward. The existence of the large-scale synoptic flow from land to sea results in an initial development out at sea. The intensification and advance of the sea-breeze landward is much more gradual and reaches the coast later in the afternoon, similar to a front with a characteristic wind shift.

The sea breeze consists of a landward current adjacent to the earth's surface and a much weaker, but deeper, return flow above. The top of the landward current ranges from a few hundred meters on a mid-latitude coast to approximately 2 km along tropical coasts. The landward penetration of the sea breeze depends on the land—sea temperature difference and the large-scale synoptic flow. During ideal conditions (weak large-scale flow), the sea breeze is frequently observed as far inland as 30 to 50 km in mid-latitude regions and sometimes several hundred kilometers inland in tropical regions.

The maximum horizontal wind velocities in a sea-breeze circulation are approximately 10 m sec^{-1}, whereas the vertical velocities are about two orders of magnitude smaller. The daily maximum winds generally occur shortly after the temperature maximum.

During the latter portion of the 1950's, Fisher [7, 9] conducted a series of observational studies of the sea breeze on the coast of New York and Rhode Island. For the first time, a simultaneous set of vertical soundings of the horizontal wind and temperature were obtained during the presence of a sea breeze. A series of observation sites, aligned along a line normal to the coast, provided the data network from which a vertical cross-section of the structure of the sea breeze could be constructed.

Fisher's observational program, which was sponsored by the U.S. Army Signal Research and Development Laboratory, Fort Monmouth, New Jersey, in addition to substantiating many previously known characteristics of the sea-breeze circulation, revealed certain characteristics which had not been noted before. These new facets of the sea breeze had escaped previous theoretical investigations based upon linear analytical mathematics.

Both Fisher [8, 9] and Estoque [3, 4] formulated physical models of the sea breeze for study by means of numerical integration using electronic computers. Fisher's numerical experiments succeeded in reproducing the principal characteristics of a sea breeze in a calm environment. They also reproduced the tendency for a sudden acceleration of the onshore flow that was observed to occur during the declining stage of the circulation's life cycle.

Estoque's model was developed somewhat differently than Fisher's, with the intention of investigating the influence of variations in the over-riding synoptic flow pattern on the development of the sea-breeze circulation. The most significant characteristic of the circulation found by Estoque is the sea-breeze front. This sharp, leading edge of the sea breeze was computed when the overriding synoptic flow was set-up to oppose the landward penetration of the sea breeze. The vertical component of the velocity field was a maximum in these cases. Its magnitude was as large as 20 cm sec^{-1}.

Although the numerical results obtained by Estoque and Fisher are most interesting, they do not provide a simple representation of the sea-breeze circulation in terms of observable parameters.

2.2 Two-dimensional Model

In the first half of this study, a two-dimensional sea-breeze model was used in an attempt to determine if the results of the proposed fallout computation scheme were reasonable. This model was developed by utilizing all available observational material [7, 9] in an effort to simulate the sea breeze as closely as possible in an x, z-plane. To take into account the development of the sea breeze, the parameters influencing the wind field are considered functions of time. Because parameters governing the position and intensity of the sea breeze are time-dependent in our two-dimensional model, the observational data of Fisher [7, 9]

were carefully studied so that their behavior could be expressed by simple functions. The parameters important in the development are:

(a) $\overline{X}(t)$, the location of the vertical center of the circulation in relation to the coast,

(b) $Z_T(t)$, height of the top of the circulation,

(c) $U(t)$, maximum value of the u-component of the wind in the local circulation, and

(d) $\sigma(t)$, the horizontal extent of the sea breeze.

Three parameters which appear in our basic equation as functions of time will be treated as constants as they are nearly constant according to observations. These are:

(a) $Z_h(t)$, the height of the base of the local circulation,

(b) $Z_m(t)$, height of the maximum value of the u-component in the local circulation, and

(c) $Z_F(t)$, the height of the top of the layer influenced by the sea breeze.

The values of these parameters are 0.07 km, 0.4 km, and 3.0 km respectively. A set of linear and quadratic functions was developed approximating the behavior of the other parameters. Employing these functions, the development of the sea breeze begins at hour 1000 local time, and intensifies and remains on the coast until hour 1200. The sea breeze then begins to progress inland and continues intensification until hour 1500 when it has reached peak development at a distance of 12 km inland. From 1500 to 1800 hours, the sea breeze dissipates and retrogresses toward the coast. At 1800, it is again centered on the coast, where it remains until it is completely dissipated at 2000. Incorporating these functions into the model provides us with a good approximation of a sea breeze during its entire life cycle. As it is impossible to specify the behavior of $\overline{X}(t)$ and $Z_T(t)$ with a single equation, the expressions are presented with the time periods in which they

are applicable. For convenience in evaluating the results, the coordinate system is centered on the coast. These functions are as follows:

(a) $\overline{X}$, position of center of circulation.

$$\overline{X}(t) = 0 \qquad \begin{matrix} 10 \le t < 12 \\ 18 < t \le 20 \end{matrix} \tag{2-1}$$

$$\overline{X}(t) = (-1.33t^2 + 40t - 288)\,10^5, \qquad 12 \le t \le 18. \tag{2-2}$$

(b) $Z_T(t)$, height of the top of the local circulation.

$$Z_T(t) = (0.4t - 4)\,10^5, \qquad 10 \le t < 12 \tag{2-3}$$

$$Z_T(t) = \left(-\frac{t^2}{22.5} + 1.33t - 8.8\right)10^5, \qquad 12 \le t \le 18 \tag{2-4}$$

$$Z_T(t) = (-0.4t + 8)\,10^5, \qquad 18 < t \le 20. \tag{2-5}$$

(c) $U(t)$, u-component of the wind in the local circulation.

$$U(t) = \left(-\frac{t^2}{7} + 4.1\,t - 22.6\right)10^2, \qquad 10 \le t \le 20. \tag{2-6}$$

(d) $\sigma(t)$, horizontal extent of the sea breeze.

$$\sigma(t) = (-0.88t^2 + 26.4t - 166)\,10^5, \qquad 10 \le t \le 20. \tag{2-7}$$

By using these expressions in the sea-breeze model presented below, wind fields approximating a two-dimensional sea breeze can be obtained. Figures 2-1 and 2-2 illustrate the sea breeze circulation for hours 1100 and 1500 respectively.

Because it is often found that an over-riding synoptic flow is present during the development of a sea breeze, the model presented will contain an undisturbed component of the wind, and a weak return flow above the local circulation.

Now, introducing a simple flow in a z, t-plane, we consider a wind field composed of an undisturbed part and a local circulation. The undisturbed part is assumed to be solely a component of velocity in the x-direction. The local circulation is assumed to obey the equation,

$$\frac{\partial w}{\partial z} = -\frac{\partial u}{\partial x}. \tag{2-8}$$

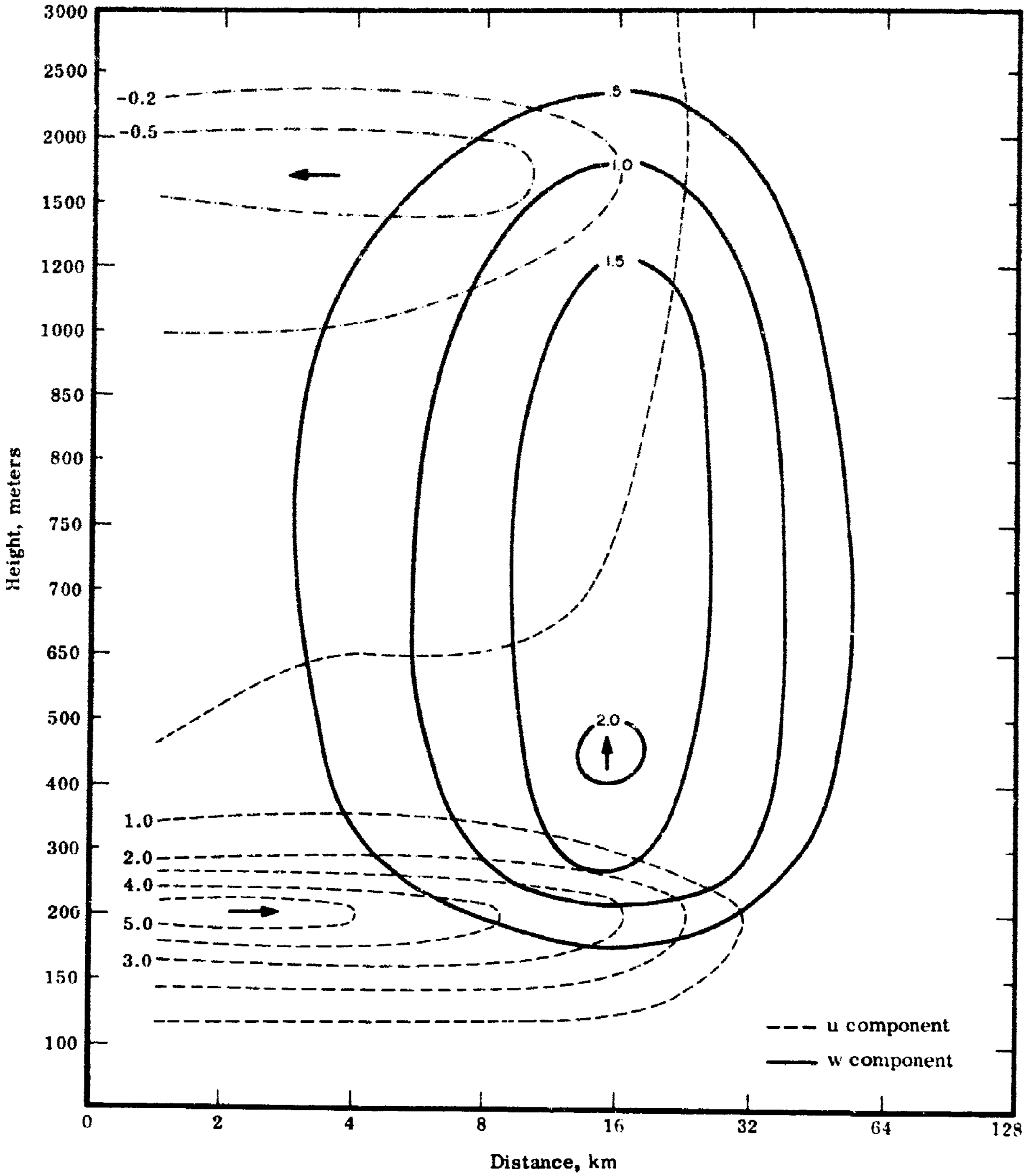

Fig. 2-1. u and w components of sea breeze at time 1100 [u (m sec^{-1}); w (cm sec^{-1})].

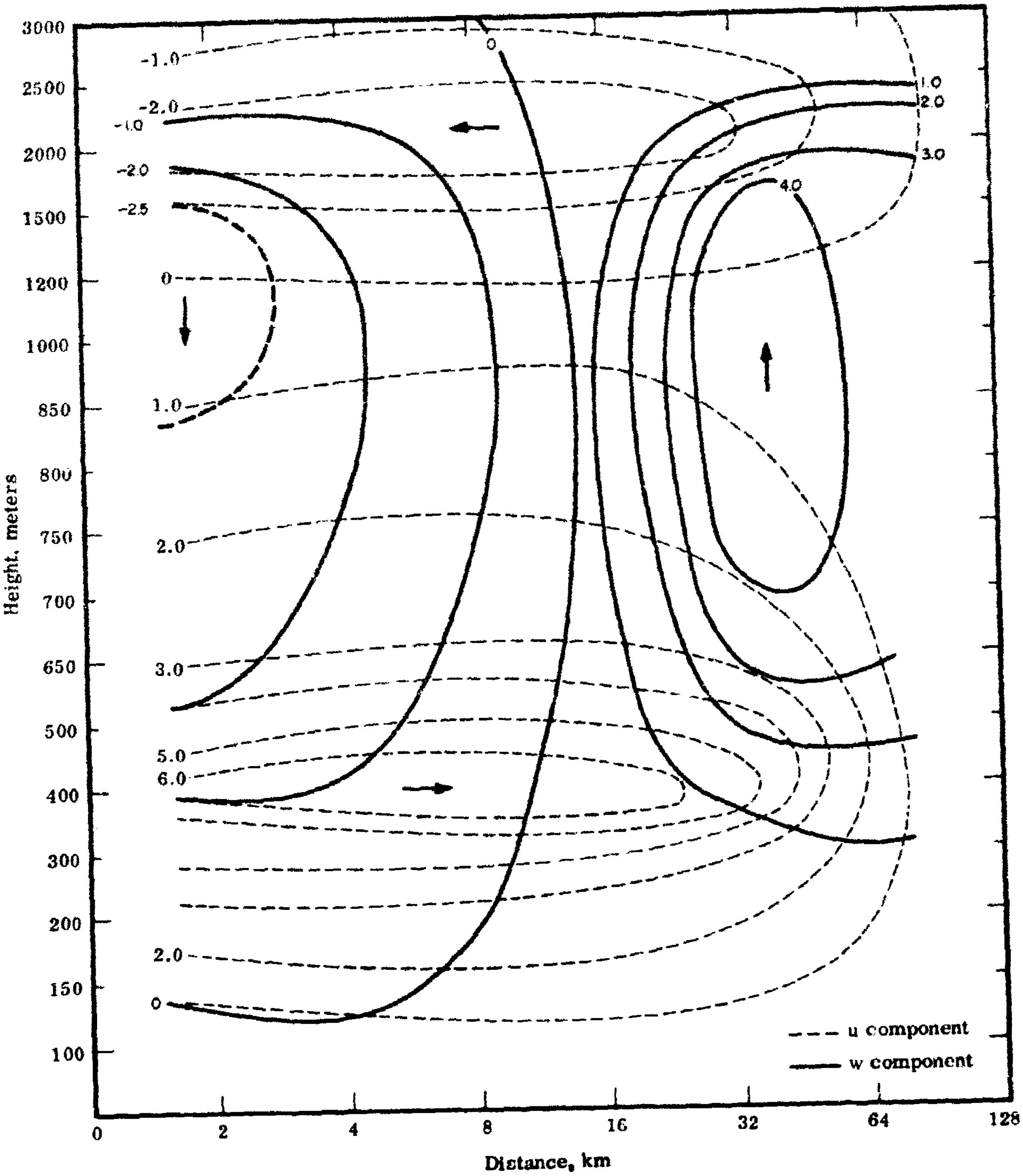

Fig. 2-2. u and w components of sea breeze at time 1500 [u (m sec^{-1}); w (cm sec^{-1})].

In this case, we will specify the u-velocity field and use it and an arbitrary boundary condition, to solve w from Eq. (2-8),

$$w = 0 \quad \text{at} \quad z = z_h \quad \text{for all} \quad x, t. \tag{2-9}$$

At this point, it is convenient to introduce the notation $\Phi(x,t)$, which is a weighting function whose value ranges between 0 and 1:

$$\Phi(x,t) = \exp\left\{-\frac{[x - \overline{X}(t)]^2}{2[\sigma(t)]^2}\right\} \tag{2-10}$$

$$\frac{\partial\Phi(x,t)}{\partial x} = -\left\{\frac{x - X(t)}{\sigma(t)^2}\right\}\Phi(x,t). \tag{2-11}$$

The total velocity components will be denoted as u and w. The undisturbed x-component will be denoted by $\bar{u}$, the local wind x-component by $\hat{u}$, and the local wind z-component by $\hat{w}$.

The equation for the undisturbed flow is:

$$\bar{u}(z) = G\left\{1 - \left[e^{-(\alpha z)}\right]\cos(\alpha z)\right\}, \tag{2-12}$$

where G is the geostrophic wind velocity, and α is the Ekman parameter $(f/2k)^{1/2}$. The equations governing the local circulation are:

$$\hat{u}(x,z,t) = 0, \qquad Z \le Z_h(t) \tag{2-13}$$

$$\hat{u}(x,z,t) = \frac{U(t)\,\Phi(x,t)\,[Z - Z_h(t)]}{[Z_m(t) - Z_h(t)]}, \qquad Z_h < Z \le Z_m(t) \tag{2-14}$$

$$\hat{u}(x,z,t) = \frac{U(t)\,\Phi(x,t)\,[Z_T(t) - Z]^2}{[Z_T(t) - Z_m(t)]^2}, \qquad Z_m(t) < Z \le Z_T(t) \tag{2-15}$$

$$\hat{u}(x,z,t) = -\,N(x,t)\,F(x,t), \qquad Z_T(t) < Z \le Z_F(t) \tag{2-16}$$

where $N(x,t)$ represents the net flow in the positive x-direction between Z_h and Z_T, and is given by

$$N(x,t) = U(t)\,\Phi(x,t)\left[\frac{Z_m(t) - Z_h(t)}{2} + \frac{Z_T(t) - Z_m(t)}{3}\right]. \tag{2-17}$$

The function, $F(z,t)$, distributes the compensating return flow normally throughout the depth Z_T to Z_F, and is given by

$$F(z,t) = \frac{1}{\sqrt{2\pi}\,\bar{\sigma}(t)} \exp\left\{ - \frac{[Z - \bar{Z}(t)]^2}{2\bar{\sigma}(t)^2} \right\}, \tag{2-18}$$

in which

$$\bar{\sigma}(t) = \frac{Z_F(t) - Z_T(t)}{4}$$

and

$$\bar{Z}(t) = \frac{Z_F(t) + Z_T(t)}{2}$$

Now from Eq. (2-8) and Eqs. (2-12) through (2-16) we find that

$$\frac{\partial \hat{w}}{\partial z} = - \frac{\partial \hat{u}}{\partial x} = 0, \qquad Z \leq Z_h(t) \tag{2-19}$$

and

$$\frac{\partial \hat{w}}{\partial z} = - \frac{\partial \hat{u}}{\partial x} = \left[\frac{X - \bar{X}(t)}{\sigma(t)^2} \right] \hat{u}(x,z,t), \qquad Z_h(t) < Z \leq Z_F(t) \tag{2-20}$$

Using the boundary condition $\hat{w} = 0$ at $Z = Z_h(t)$, we now integrate Eq. (2-20) to obtain $\hat{w}$ in the region between Z_h and Z_F.

Writing

$$\hat{w}_m = \hat{w}\ [Z = Z_m(t)],$$

we find

$$\hat{w}(x,z) = \left[\frac{X - \bar{X}(t)}{\sigma(t)^2} \right] \Phi(x,t)\, U(t)\, \frac{[Z - Z_m(t)]^2}{2[Z_m(t) - Z_h(t)]}, \tag{2-21}$$

$$Z_h(t) < Z \leq Z_m(t)$$

$$\hat{w}(x,z) = \hat{w}_m - \frac{X - \bar{X}(t)}{\sigma(t)^2} \frac{\Phi(x,t)\, U(t)}{3[Z_T(t) - Z_m(t)]^2} \left\{ [Z_T(t) - Z]^3 - [Z_T(t) - Z_m(t)]^3 \right\}, \qquad Z_m(t) < Z \leq Z_T(t). \tag{2-22}$$

Now writing

$$\hat{w}_T = \hat{w}\ [Z = Z_T(t)],$$

we find

$$\hat{w}(x,z) = \hat{w}_T - \frac{N(x,z)}{\sqrt{2\pi}\,\bar{\sigma}(t)} \left\{ \int_{Z_T}^{Z} \exp\left[- \frac{[Z - \bar{Z}(t)]^2}{2[\bar{\sigma}(t)]^2} \right] dz \right\} \left[\frac{X - \bar{X}(t)}{\sigma(t)^2} \right], \tag{2-23}$$

$$Z_T(t) < Z \leq Z_F(t).$$

2.3 Three-dimensional Model

As was mentioned earlier, local circulations are three-dimensional in nature and their dimensions are strongly time dependent. The two-dimensional model described above was developed to test the computation scheme used. However, our final objective in this study is to develop three-dimensional, kinematic local circulation models and to compute the influence of such local winds on the pattern of close-in fallout deposition. This requires that we be able to describe quantitatively the three velocity components of natural antitriptic wind fields in terms of a limited number of observable parameters. Because observational material of the sea breeze in three dimensions are non-existent, we have turned to the results of theoretical studies in an effort to seek such representations of the sea breeze. In the work of Pierson [14] and Haurwitz [11], we have found compatible studies of temporal and spatial structure of the sea breeze. Although the formulas derived from their work are complicated, we must emphasize that they do not admit representation of the non-linear characteristics of the sea breeze found in the physical models of Estoque and Fisher. The generation of three-dimensional, time-dependent wind fields from the theoretical solutions obtained both analytically and numerically will require the imaginative manipulation of the solutions to fit the limited observational data. Although we have initiated this work, it would be premature to report upon it in detail at this time.

3.0 THE FALLOUT CLOUD

3.1 Review of Literature

Since the advent of atomic weapons, numerous studies have been conducted dealing with the problem of both close-in and distant fallout. To date, one of the most perplexing problems still confronting investigators is the distribution of radioactive particles within the stem and mushroom cloud. Kellogg, Rapp, and Greenfield [12] made some estimates of particle distribution based on observed fallout and a reconstruction of what the initial distribution must have been. However, in reconstructing the initial distribution, two assumptions were made:

(a) Ten percent of the debris was distributed evenly throughout the stem and the remaining portion was in the mushroom cloud.

(b) The particles in the cloud were distributed in such a way that there was a constant mixing ratio between the particles and the air.

This would mean that there was complete mixing in the mushroom cloud of 90 percent of the particles and, therefore, the density of the particles drops off exponentially with height in exactly the same way as the air density. In the stem this is not true, and it can be seen that a constant density of particles with height implies a mixing ratio that increases with height. That is, relative to the air, there are more particles in the top of the stem than in the lower part.

Anderson [1], in a theoretical study, found that close-in fallout is comprised mainly of particles with significant gravitational fall velocities which are best defined in terms of a minimum particle size of about 50 microns in diameter. Particles smaller than this exhibit a rapid decrease of fall speed with decrease of size. Consequently, the particle sizes important in close-in fallout range from 500 microns to 25 microns in radius.

Machta [13], in a study of the dimensions of an atomic cloud, developed a semi-empirical theory relating the dimensions to atmospheric stability and the rate of entrainment. This semi-empirical theory, although widely used, provides only rough estimates; however, as there is a current lack of a more accurate theory, cloud dimensions used in our study are based on it.

3.2 Computation of Fallout in a Two-dimensional Model

In computing the motion of a fallout cloud through a sea-breeze circulation, the governing factors are the horizontal and vertical wind velocities and the fall speed of the particles contained within the cloud. In formulating this portion of the problem, we considered a rather simple scheme whereby the fallout cloud was divided into n slices. Each slice contained a specified fraction of the total mass which was assumed to be uniformally distributed throughout the slice. At this stage, we prescribed a finite number of points describing the boundary of each slice. The slices are then allowed to descend through the local circulation with a given fall velocity until all the slices have been deposited. This procedure is repeated using a spectrum of fall velocities.

In determining the trajectory of the cloud, or slices in our case, the u and w wind components must be computed at the points describing the slices. Having obtained the wind components at these points, the horizontal and vertical displacements of the points are computed for a given time interval (Δt) by using the following formulas:

$$\Delta x = u\Delta t$$

and

$$\Delta z = (w + VF)\,\Delta t$$

where VF = fall velocity of particles (VF < 0).

After computing the displacements and obtaining a new set of coordinates for the points describing the slice, the process is repeated until all slices have been deposited on the surface. However, it is possible that the distance between two adjacent points on the slice boundary may become too large, thus making the results unreliable. Therefore, a set of limits was established whereby if the distance between any two adjacent points exceeds these values, the iteration for that particular time step will be repeated using half the original value of Δt. If the points are still too widely separated after three iterations, the program is terminated for that particular fall velocity.

During the time of descent through the local circulation, the area of the slice must be computed after each time step because the area may change due to contraction or expansion, depending upon the displacement of the points. Having

specified the mass within the slice, the density can be computed. At the time deposition commences, the area of the slice found below the ground must be computed so that the mass of material deposited can be determined using the density value from the previous time step. The fallout is then assigned to that particular interval on the x-axis. The total mass is now modified by subtracting the amount of mass that has been deposited. The area of the slice remaining above the ground is computed and, using the modified mass, a new density is determined. At this stage, the points that descended through the surface are now replaced by points on the surface vertically above them, so that the number of points defining the slice remains unchanged. The remaining portion of the initial slice is now resting on the ground. The u and w wind components are again computed for all the points. Once deposition begins, the points resting on the surface can only move vertically downward. This procedure is continued until the slice has been completely deposited (see Appendix A).

Because the fallout cloud was initially divided into n slices, each slice must be treated individually until all slices have been deposited.

3.3 Computation of Fallout in the Three-dimensional Model

In formulating the three-dimensional problem, we initially considered a rather complex scheme for computing both the motion of the fallout cloud and the changes in the concentration of the fallout within the cloud. The procedure would generalize the two-dimensional scheme utilized in the computations reported above. The surface of the fallout cloud would be approximated by a polyhedron with triangular faces and the vertices of the polyhedron cloud would be associated with several of the triangular faces. By proper indexing of the vertices and facets, the interior of the cloud could be determined throughout the trajectory computation. A principal advantage of this scheme would have been its capacity for admitting computation of changes in the fallout concentration within the cloud.

Subsequent consideration, however, led us to decide on utilizing the simplifying assumption that the fallout concentration was conserved during the motion of the cloud. Consistent with this assumption is a simpler description of the cloud and a simpler trajectory computation procedure, somewhat similar to that used in the Ford model [15].

The stabilized cloud, which we will assume to be cyclindrical with stem and mushroom cap, is divided into discs. Each disc is assumed to enclose a specified fraction of the total radioactive mass of the entire cloud. This fractional mass content is further assumed to be distributed according to a particle size spectrum appropriate to the position of the disc within the cloud.

At this point, a further assumption is made that the continuous particle size spectrum may be replaced by a discrete and finite line spectrum. A unique fall velocity corresponds to each line in the spectrum. Thus, to compute the motion of the material originally within a particular disc, the disc must be replaced by as many sub-discs (wafers) as there are lines in the discrete spectrum.

When the center of gravity of the disc is at an altitud^ above which local circulations are allowed, we move each wafer with the wind field existing at its center of gravity. When the center of a wafer reaches an altitude below which local circulations are permitted, we further subdivide* the wafer into smaller volume elements. Then each element is followed through the local circulation until deposition occurs. The position of deposition and the quantity of material deposited is recorded and the computation continued.

*Refer to Appendix C for subdivision scheme.

4.0 COMPUTED EFFECTS OF THE SEA-BREEZE CIRCULATION ON THE FALL-OUT DISTRIBUTION

4.1 Background

The fallout distribution depends upon the circulation through which the particles must descend. Several experiments were performed whereby clouds of various dimensions and containing the spectrum of particle sizes were simulated to descend through the circulation produced by the sea-breeze model. It will be noted at this point that, in these experiments, we are dealing solely with the mushroom cloud and not the stem, as information pertaining to its dimensions and particle size distribution is lacking. The dimensions of the mushroom cloud, particle size distributions, and associated terminal velocities were obtained from the investigation of Kellogg, Rapp, and Greenfield [12]. Two different cloud sizes were used in the experiments, resulting from yields of 10 kt and 300 kt. In the 10 kt yield, the cloud is 2.4 km in diameter and 1.2 km thick. For the 300 kt yield, the cloud is 15 km in diameter and 5 km thick. The clouds were divided into discs 0.61 km and 1 km thick, respectively. Therefore, in the 10 kt and 300 kt cases, we computed the descent of two and five discs respectively, through the local circulation. The particle sizes used in both cases ranged from 300 to 25 microns, with associated terminal velocities of 500 cm sec^{-1} to 25 cm sec^{-1}. The base of the clouds were initially at 3 km above the surface.

The initial position of the cloud in relation to local circulation will produce different fallout distributions, and the experiments were designed with this in mind. Basically, two different circulations were used, (1) sea-breeze circulation imbedded in an over-riding synoptic flow from the sea to land, and (2) a sea-breeze circulation in the absence of an over-riding synoptic flow. The positions of the 10 kt yield experiments were: (1) 1.6 km out at sea, and (2) directly over the coast line. Similarly, the positions of the 300 kt yield experiments were: (1) 15 km out at sea, and (2) directly over the coast line. In the analysis of the results, the fallout distributions were identical in both cases (cloud located offshore and on-coast), except that they were shifted. The position and configuration of the cloud is a variable in this model, (x- and z- coordinates describing cloud) and, therefore, any number of experiments may be performed with the computer program.

To investigate the effect of the circulation on the fallout distribution, the assumption was made that each disc was a homogeneous layer of particles with uniform fall velocities. Nine different fall velocities were used and are presented in Table 4-1.

TABLE 4-1
FALL VELOCITIES

Radius (μ)	Terminal velocity (cm sec^{-1})
300	500
250	400
175	300
125	200
90	150
70	100
60	75
40	50
25	25

Each disc was allowed to descend through the local circulation nine times. Because information relating the mass of particles contained within a cloud to weapon yield is lacking, a value of 100 was used. This permits us to express the distribution of fallout on a surface as a percentage of the total mass contained within the cloud.

4.2 Local Circulation in the Absence of an Overriding Flow

Two experiments were performed in which clouds from a 10 kt and 300 kt yield were simulated to descend through a sea-breeze circulation in the absence of an overriding flow. Figure 4-1 illustrates the distribution of fallout as a result of a cloud produced from a 10 kt yield, located 1.6 km out to sea, and simulated to descend through the local circulation (solid line) and the resulting distribution in the absence of any circulation (stipple area). In this case, the simulated local circulation modified the fallout pattern to the extent that approximately 50% of the

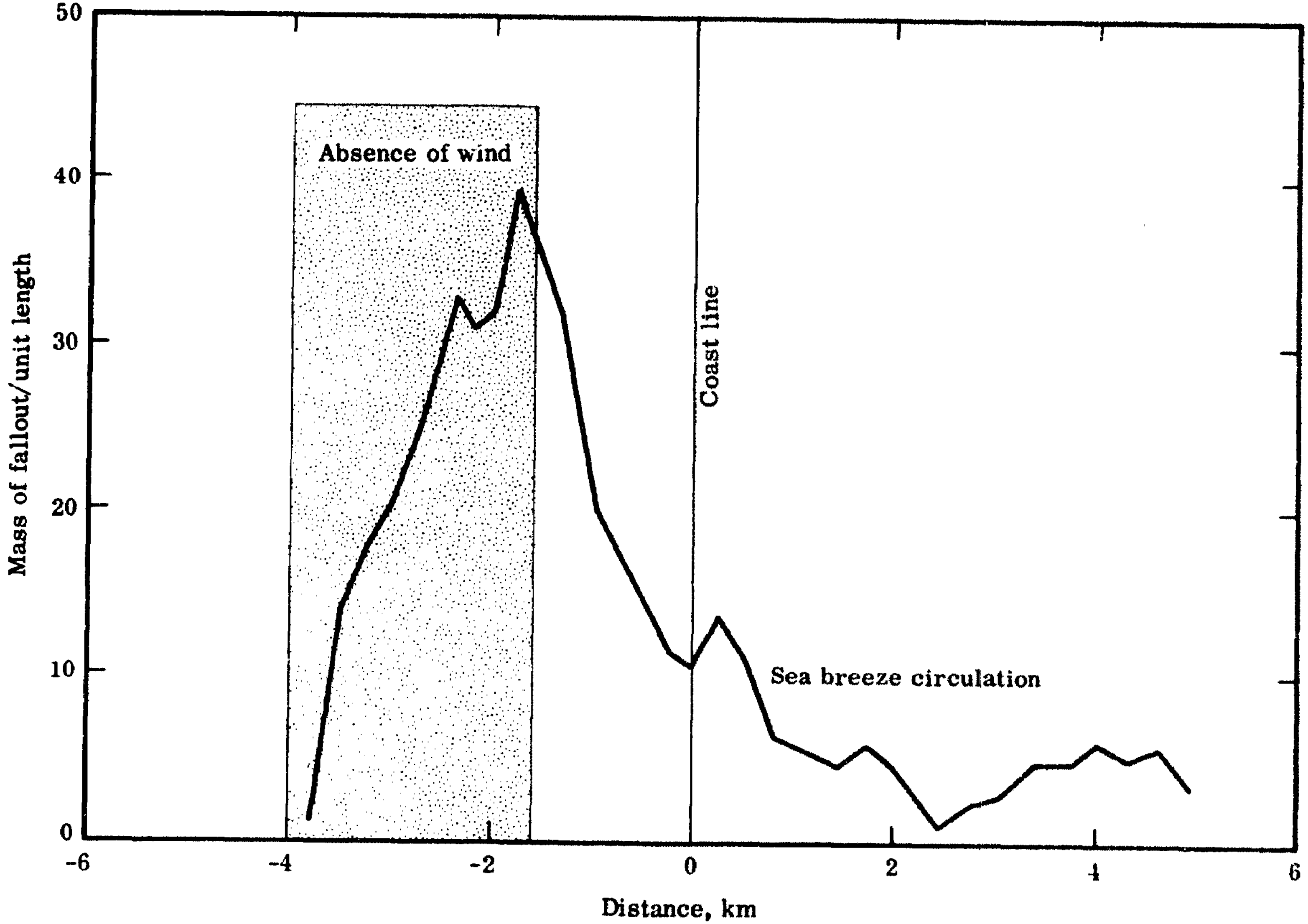

Fig. 4-1. Fallout distribution from a 10-~~kt~~-yield burst located offshore with no overriding flow.

mass was distributed outside of the area directly beneath the initial position of the cloud. In the second case (see Fig. 4-2), a cloud from a 300 kt yield and located 15 km out to sea, had only 10% of its mass transported away from the initial position. Particles with fall velocities of less than 100 cm sec^{-1} were influenced to a greater degree than larger particles, as was shown by Feteris [6]. The experiments conducted included particles with fall velocities of 25 cm sec^{-1} However, after 3 hours of real time, deposition had not occurred and the points described in the boundary of the slice become too widely separated to fall within the specified limits after three iterations; therefore, the program was terminated for that particular fall velocity. This happened because the particles with fall velocities of 25 cm sec^{-1} and less are greatly influenced by the local circulation and, had we assigned extremely large limits, deposition would have occurred. The results however, would have been unreliable.

4.3 Local Circulation in an Overriding Flow

Two experiments were also conducted using a local circulation imbedded in an overriding flow. The positions of the clouds were, as before, (1) 10 kt yield, 1.6 km offshore, and (2) 300 kt yield, 15 km offshore.

In the 10 kt yield experiment, the fallout distribution was quite different from the pattern obtained from the local circulation only. The fallout was distributed over a larger region (27 km) primarily due to the overriding flow. The distribution of fallout was also computed in this case for an overriding flow without the local circulation. Figure 4-3 shows that the local circulation did influence the fallout pattern, producing peaks and minimums in relation to the distribution obtained solely from the overriding flow. The sea breeze in this case did influence the fallout pattern; however, it should be kept in mind that with a very weak overriding flow (of the order of 1 cm sec^{-1}), the local circulation may have a greater influence on the fallout distribution.

In the case of the 300 kt yield burst (cloud location was 15 km offshore), the fallout distribution was greatly influenced by the overriding flow (5 m sec^{-1}) because the area covered by fallout was quite large (92 km). Figure 4-4 shows that a marked peak exists between the coast and the initial position of the cloud. This results from particle sizes with fall velocities greater than 100 cm sec^{-1}.

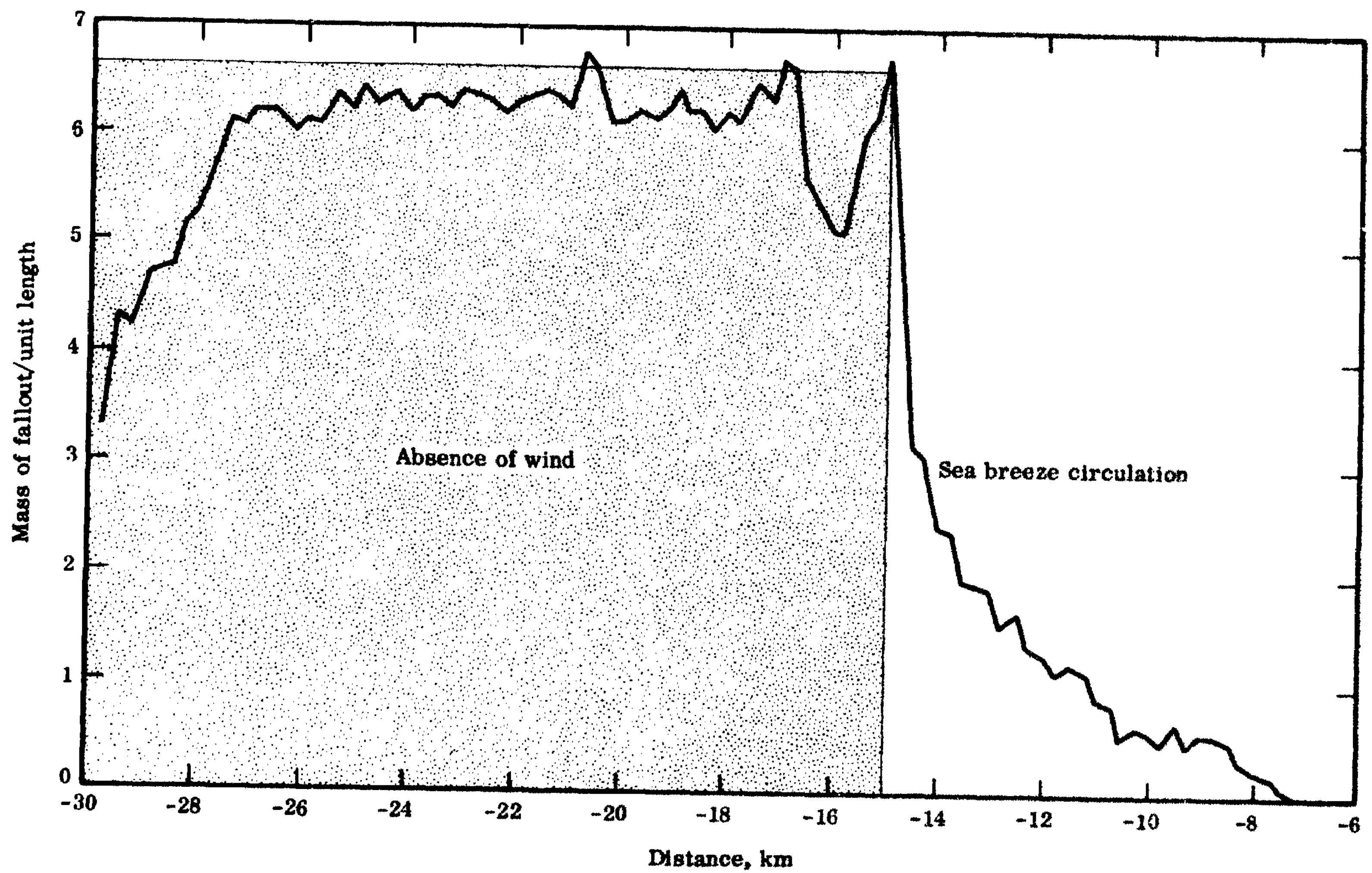

Fig. 4-2. Fallout distribution from a 300-kt-yield burst located offshore with no overriding flow.

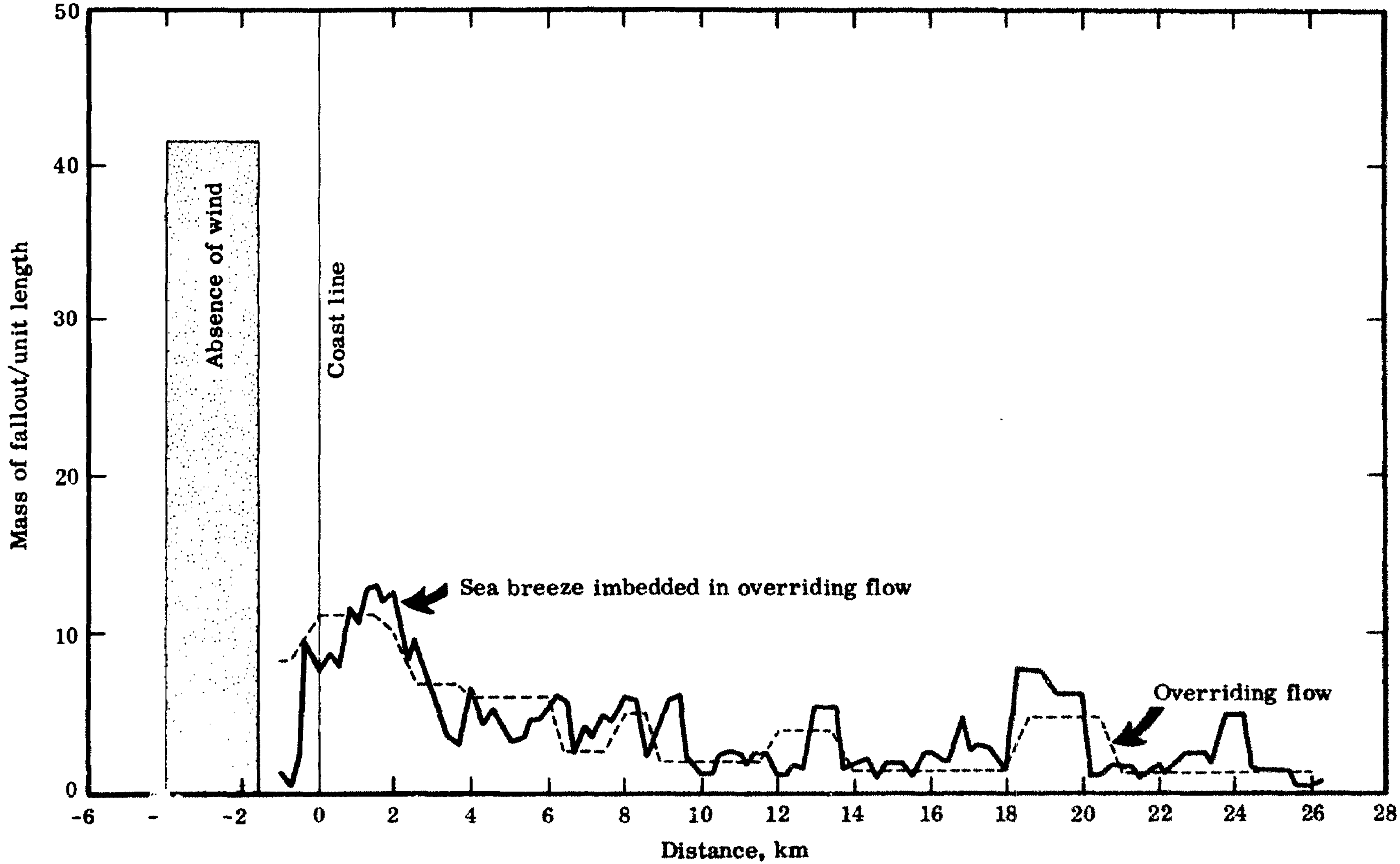

Fig. 4-3. Fallout distribution from a 10-kt-yield burst located offshore with an overriding flow of 5 m sec^{-1}.

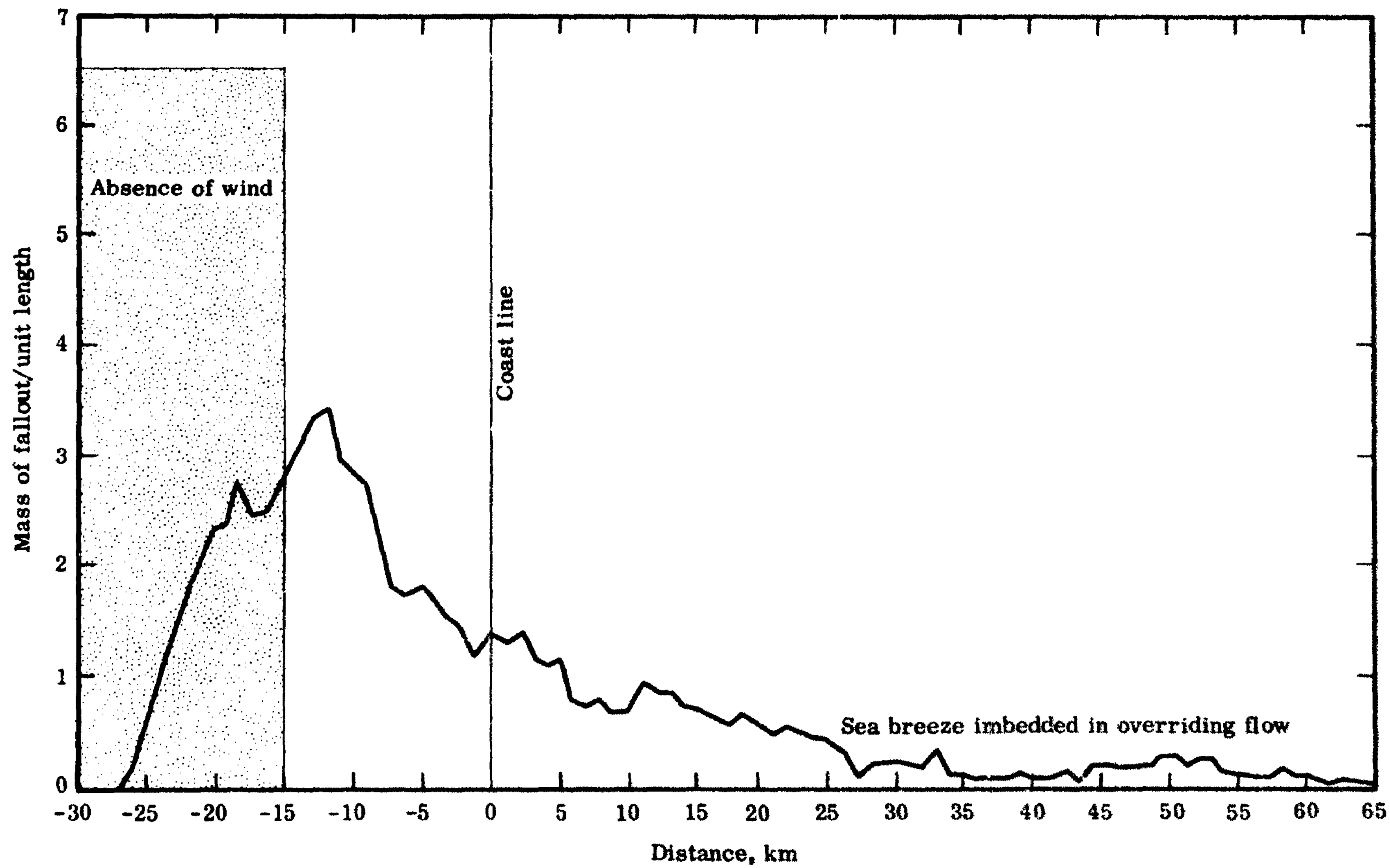

Fig. 4-4. Fallout distribution from a 300-kt-yield burst located offshore with an overriding flow of 5 m sec^{-1}.

5.0 CONCLUSIONS

The primary objective in this study is to develop three-dimensional local circulation models for computation of close-in fallout patterns. In the development of a two-dimensional sea-breeze model, it has been demonstrated that such models can be expressed in terms of analytical functions and can be readily programmed for rapid computation of fallout distributions as influenced by such circulations. Also, the results obtained by Feteris [6] by hand computations have been verified by using an automated two-dimensional sea-breeze model.

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7.0 PROGRAM FOR THE NEXT INTERVAL

As indicated above, we have initiated the formulation of a three-dimensional, time-dependent kinematic model of the sea-breeze wind field. This work will continue and very likely be extended to consider models of the mountain-valley wind. A new computer program, based on the logic outlined in Section 3.3 and Appendix C, will be written. Finally, numerical results will be obtained from experiments judiciously designed to indicate the influence on the deposition of close-in fallout exerted by the kinematic, local wind models.

8.0 IDENTIFICATION OF PERSONNEL

8.1 Extent of Participation

TABLE 8-1
PERSONNEL PARTICIPATION*

Name	Title	Total hours worked during the quarter (approximate)
J. P. Gerrity	Principal Investigator	232
J. D. Kangos	Project Scientist	673
E. A. Newburg	Mathematician	45
P. S. Brown	Mathematician	38
A. F. Saunders	Programmer	12
J. A. Sekorski	Programmer	237

*Secretarial, administrative, and drafting assistance was also provided.

8.2 Biographies of Key Personnel

Joseph P. Gerrity, Jr., M.S.

Professional Experience

A Research Scientist in the Planetary Dynamics Divison, Mr. Gerrity has served as principal investigator on projects involved in the development of physical models of the planetary boundary layer and of kinematic models of the influence of local circulations upon radioactive fallout patterns. He has also participated in research projects investigating tropical weather analysis and prediction, and large-scale cloud prediction.

From 1957 to 1962, he was employed by the Research Division of the College of Engineering of New York University, where he served as director of the Cyclone Development Project, which investigated the influence of diabatic processes on cyclogenesis.

Before 1957, Mr. Gerrity was employed by the General Electric Co. as a systems analyst, at its Advanced Electronics Laboratory in Ithaca, N.Y.

While on active duty with the U.S. Air Force (1952—1956), he served as a weather officer at L.G. Hanscom Field, Bedford, Mass., for three years.

Educational Background

Mathematics, B.A. ('52), Manhattan College
Meteorology, M.S. ('59), New York University

Professional Affiliations

American Meteorological Society
American Geophysical Union

Technical Publications

Some Results of Experiments with an Integrated, Wet, Diabatic Weather Prediction Model (with J. Spar and L.A. Chhen). Sci. Rpt. 2, Contract Nonr 285-(09), Res. Div., Col. of Eng., New York Univ., Jun. 1961.

A Survey and an Appraisal of Large-scale Physical Cloud Prediction (with Arnason and Pavlowitz). Tech. Rpt. 3, Contract AF19(626)-16, Travelers Research Center, Inc., Feb.1963

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Mechanisms Important to the Formation, Movement, and Dissipation of Low Clouds. Tech. Memo. 7045-92, Contract AF19(626)-16, Travelers Research Center, Inc., Sep. 1963

A Physical Model for the Prediction of Large-scale Low Cloudiness. Tech. Rpt. 7463-150. Contract AF19(628)-3437, Travelers Research Center, Inc., Feb. 1965

James D. Kangos, M.S.

Professional Experience

Mr. Kangos is an Associate Scientist in the Planetary Dynamics Division of the Atmospheric and Oceanographic Sciences Department. Presently, he is developing kinematic sea-breeze models for application in close-in fallout. Prior to this he was responsible for the application of power spectrum analysis to detect and describe tropical perturbations, and he planned and supervised the development of an input data handling technique for the processing of hourly aviation weather reports for use in Weather System 433L and the Common Aviation Weather System.

Before joining the Research Center, Mr. Kangos was employed by the Office of Meteorological Research of the U.S. Weather Bureau in Washington, D.C., where he conducted studies of the heat flux over the oceans in Antarctic regions.

From 1957 through 1959, Mr. Kangos was associated with the Research Division of New York University, studying upper-air observations taken in the Antarctic. Mr. Kangos served as a forecaster in the Air Weather Service.

Educational Background
Meteorology, B.S. ('57), New York University
Meteorology, M.S. ('59), New York University

Professional Affiliation
American Meteorological Society

Technical Publications

An Analysis of Upper-Air Observations at McMurdo Sound, Antarctica, Sci. Rpt. 7, Contract AF19(604)-1755, Research Div., College of Engineering, New York Univ., Jul. 1959.

"A Preliminary Investigation of the Heat Flux from the Ocean to the Atmosphere in Antarctic Regions," J. Geophys. Res., 1960.

Some Estimates of Power Spectra of Synoptic-scale Perturbations in the Tropical Pacific, 7459-142, The Travelers Research Center, Inc., Hartford, 1964.

Edward A. Newburg, Ph.D.

Professional Experience

Dr. Newburg is a Research Scientist in the Atmospheric and Oceanographic Sciences Department of The Travelers Research Center, Inc. He is responsible for the analysis of mathematical problems which originate in the various Divisions of the Research Center and for the initiation of research in mathematical problems relevant to all areas of the environmental sciences.

From 1958 to 1961, Dr. Newburg was a mathematician in the Nuclear Division of Combustion Engineering, Inc. His work there included formulation of mathematical models for the physical description of neutron chain reactors. Much of his effort was devoted to the numerical solution and/or qualitative analysis of equations describing the kinetics and dynamics of power reactor systems.

Since 1960, Dr. Newburg has been an Adjunct Assistant Professor of Mathematics at the Hartford Graduate Division of Rensselaer Polytechnic Institute. Prior to 1958, he was a part-time teaching assistant in the mathematics departments of the University of Illinois and Purdue University. During the summers of 1953, '54, '55, and '57, he was employed by the Allison Division of the General Motors Corporation, where his highest position was project engineer.

Educational Background

Mathematics and Physics, B.S. ('52), Purdue University
Mathematics, M.S. ('53), Purdue University
Mathematics, Ph.D. ('58), University of Illinois

Professional Affiliations

American Mathematical Society
Mathematical Association of America
Society of Industrial and Applied Mathematics

Technical Publications

"Potential Representations in Integral Equations," Ph.D. thesis, Univ. of Illinois, 1958.

"Xenon Oscillations" (with P. B. Daitch), Combustion Engineering TP-26, 1959.

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Relationships Between Tropical Precipitation and Kinematic Cloud Models (with E. Kessler, III, P. Feteris, and G. Wickham) Quart. Prog. Rpt. 4, Contract DA-36-039 SC 89099, U.S. Army Signal R & D Lab., The Travelers Res. Center, 1963.

Philip S. Brown, Jr., S.M.

Professional Experience

Mr. Brown was appointed to the position of Research Associate of The Travelers Research Center, Inc. in September 1963.

In 1961 he received his bachelor's degree from Wesleyan University where he majored in mathematics and was employed through NSF Funds for study in linear algebra. In 1963 he received his master's degree from MIT where he worked in pure and applied mathematics. His course of study turned toward the subject of hydrodynamics, and his thesis was concerned with the Benard Convection Problem. Since joining The Travelers Research Center, he has worked in various areas involving applications of mathematics to meteorological problems; these applications have included work in the fields of numerical, complex, and real analysis.

Educational Background

Mathematics, B.A. ('61), Wesleyan University
Mathematics, S.M. ('63), Massachusetts Institute of Technology

Professional Affiliations

The Mathematical Association of America
The American Mathematical Society

Technical Publications

"Thermal Convection," Master's Thesis, M.I.T., 1963.
Theoretical and Synoptic Studies of Low-level Tropical Perturbations, (with G. Árnason, K. D. Hage, and G. M. Howe), Final Rpt. 7461-147, Contract Cwb-10759, The Travelers Research Center, Hartford, Nov. 1964.

Alexander F. Saunders, B.S.

Professional Experience

Mr. Saunders is an analyst in the Data Processing Division of the TRC Service Corporation. His duties include the analysis and development of computer techniques and programs applicable to the solution of various engineering, scientific, and data-processing problems. Computers used in accomplishing these solutions include the IBM 1620, 7080, 7090, and 7094.

Previously, Mr. Saunders directed IBM 1620 computer operations at the Morgan Construction Co., Worcester, Mass. He was responsible for the analysis of mechanical systems, associated computer solutions, and the conduct of employee programmer-training sessions.

From 1960 to 1961, Mr. Saunders was employed at the United Aircraft Research Laboratory, East Hartford, Conn., where he programmed a variety of gas-turbine, rocket, and data-reduction problems for solution on the IBM 7090 and Philco 2000 computers. He was also involved with the use of Philco 2000 nuclear codes and with instruction in programming for new employees.

Experience previous to this was gained at the Royal McBee research facility, West Hartford, Conn. His functions there included the analysis of a variety of mechanical and electrical problems and the programming of their solution on an LGP-30 computer.

From 1954 to 1958, Mr. Saunders was associated with Pratt & Whitney Aircraft, East Hartford, Conn., where he was attached to a number of engine-performance analytical groups. His duties included the implementation of engine tests, test-data analysis and performance prediction, and programming for the IBM 704.

Educational Background
Engineering, B.S. ('63), University of Hartford

Professional Affiliation
Association for Computing Machinery

J. A. Sekorski

Professional Experience

Mr. Sekorski is a Staff Associate in the Planetary Dynamics Division of the Atmospheric and Oceanographic Sciences Department. He has been an active programmer for the past two years. His work includes programs written in complex arithmetic necessary for computations of solutions in air-sea interaction and tropical perturbation problems.

Prior to joining the Research Center in 1959, Mr. Sekorski served as an observer and as a chief observer in the Air Weather Service. He received training at Chanute Air Force Base, Rantoul, Illinois.

APPENDIX A

SPECIFICATIONS FOR COMPUTATION OF FALLOUT FROM A TWO-DIMENSIONAL CLOUD IN A TWO-DIMENSIONAL WIND FIELD

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APPENDIX A. SPECIFICATIONS FOR COMPUTATION OF FALLOUT FROM A TWO-DIMENSIONAL CLOUD IN A TWO-DIMENSIONAL WIND FIELD

A.1.0 INTRODUCTION

This is a set of program specifications for the first in a series of computer programs to be used to evaluate the influence of local wind circulations on the deposition of close-in fallout. This program is designed to treat a two-dimensional cloud of uniform-size fallout particles initially contained within the first few kilometers above the earth's surface.

The program was written in FORTRAN for the IBM 7094 digital computer. Machine time requirements may be estimated from the following result. Three minutes of machine time were required to deposit, from a height of 4 km, eight wafers (one wafer for each of eight particle sizes). Each wafer was defined by twenty-four points on its boundary.

A.2.0 INPUT

Basic input will be from cards and is defined as follows:

G	Geostrophic wind speed, cm sec^{-1}	X.XXEXX
A	Ekman spiral parameter, cm^{-1}	X.XXEXX
XC	Critical separation tolerances, cm	X.XXEXX
YC	Critical separation tolerances, cm	X.XXEXX
XP(K)	Coordinates of points on cloud at the initial time, cm	X.XXXXEXX
YP(K)	Coordinates of points on cloud at the initial time, cm	X.XXXXEXX
KMX	The number of points defining the cloud	
XMASS = TØTMAS	The mass of fallout material within the cloud at the initial time, gms	X.XXXXEXX
DT	The time step to be used in computing movement of the cloud, initially sec	X.XXXXEXX
TØUT(I)	The times at which the configuration of the cloud is to be outputted, (I < 50) sec	X.XXXXEXX
VF	The fall speed of the cloud particles relative to the air (negative number), cm sec^{-1}	X.XXEXX

A.3.0 COMPUTATIONS

The main program consists of a series of subroutine calling statements, plus a scheme for condensing output from the subroutine DPOSIT. Once deposition commences, the subroutine DPOSIT outputs deposition values after each time step. For convenience in evaluating these results, a scheme was developed and incorporated into the main program; the scheme takes the outputs from all the time steps and orders and condenses them into a single output in tabular form and with proper heading identifications.

All computations are performed in the subroutines except for the ordering and condensing of the output from subroutine DPOSIT, which take place in the main program. All parameters are stored in common. A description of each subroutine is presented below, followed by the calling sequence logic (Fig. A-1).

A.3.1 Subroutine XINPW

The purpose of this subroutine is to compute all time-dependent parameters such as U, YT, S, and XB which are input for the WIND program. These parameters will be computed at increments of 1800 seconds. T is the time step in seconds, and we let TD be the time of day. Whenever T = 1800 sec, then the time of day (TD) will be increased by 0.5 and the four parameters mentioned above will be recomputed.

Output of this routine will be stored in common for use as input to the WIND routine. An initial TD will be given and T = 0 at the start. Compute the following to be used as input:

$$S = [-0.88(TD)^2 + 26.4(TD) - 166]\ 10^5$$

$$U = [-0.143(TD)^2 + 4.086(TD) - 22.571]\ 10^5$$

If

$10 \leq TD < 12$, go to A

$12 \leq TD \leq 18$, go to B

$18 < TD \leq 20$, go to C

A. $XB = 0$

$YM = 0.7 \times 10^4$

$YT = [0.4(TD) - 4]\ 10^5$

B. $XB = [-1.33(TD)^2 + 40(TD) - 288]10^5$

$YM = 0.7 \times 10^4$

$YT = [-0.044(TD)^2 + 1.33(TD) - 8.8]10^5$

C. $XB = 0$

$YM = 0.7 \times 10^4$

$YT = [-0.4(TD) + 8]10^5$

A.3.2 Subroutine WIND

The purpose of this routine is to compute, using analytical formulas, the u and w components of the wind field at the points describing the slice. The parameters required as card inputs are Z_h, Z_m, Z_F, A, G, SP(K), and YP(K). The parameters Z_T, U(t), $\overline{X}$(t), and (t) are computed in subroutine XINPW and, through the main program, are available for use in the subroutine. At this point it should be mentioned that the notations used in the computer program and in the text of this report differ in some instances. These differences are listed below.

Text	Program	Text	Program
Z_h	YH	$\overline{\sigma}$	SB
Z_m	YM	U(t)	U
Z_F	YF	$\overline{u}$	UBAR
α	A	$\hat{u}$	U(K)
G	G	$\hat{w}$	V(K)
X	XP(K)	Φ	PHI
$\overline{X}$	XB	Z	YP(K)
σ	S	Δt	DT
Z_T	YT		
$\overline{Z}$	YB		

The output of this subprogram will be the quantities U(K) and V(K) of the wind components in the x and y directions, respectively, at point K where $1 \leq K \leq KMX$.

Compute the following to be used as input.

$$SB = \frac{YF - YT}{4}$$

$$YB = \frac{YF + YT}{2}$$

Let K = 1, ..., KMX

If YPK $\leq$ YH, go to A

YPK > YH, compute

$PHI = \exp\ [-(XPK - XB)^2/2S^2]$ and store,

$HD = [(PHI)U]/[3(YT - YM)^2]$ and store,

$XD = (XPK - XB)/S^2$ and store,

$VM = (XD)\ (PHI)\ U(YM - YH)/2$ and store,

$VT = VM - (XD)\ (HD)\ [-(YT - YM)^3]$ and store,

$XN = U(PHI)\ (\frac{YM - YH}{2} + \frac{YT - YM}{3})$ and store,

$UBAR = G\ [1 - (e^{-AYPK})\cos (AYPK)]$ and go to B.

A. Compute

$UHAT = 0$

$UBAR = G\ [1 - (e^{-AYPK})\cos (AYPK)]$

$VK = 0$

$UK = UBAR$

B. If YPK $\leq$ YM, go to 1

YPK > YM, go to C

1. Compute

$UHAT = U(PHI)\ (YPK - YH)/(YM - YH)$

$VK = (XD)\ (PHI)\ U(YPK - YH)^2/2(YM - YH)$

$UK = UBAR + UHAT$

C. If YPK $\leq$ YT, go to 1

YPK > YT, go to D

1. Compute

$$UHAT = U(PHI)\,(YT - YPK)^2/(YT - YM)^2$$

$$VK = VM - (XD)\,(HD)\,[(YT - YPK)^3 - (YT - YM)^3]$$

$$UK = UBAR + UHAT$$

D. If $YPK \leq YF$, go to 1

$YPK > YT$, then set $U(K) = G\,[1 - (e^{-AYPK})\cos(AYPK)]$

and evaluate scheme for EY where

$$EY = \int_{YT}^{YPK} \exp\left[-\frac{(Y - YB)^2}{2(SB)^2}\right] dY$$

1. Compute

$$XF = \frac{1}{\sqrt{2\pi}\,(SB)} \exp\{-(YPK - YB)^2/[2(SB)^2]\}$$

$$UHAT = (XN)\,(XF)$$

$$VK = VT - XN/[\sqrt{2\pi}(SB)]$$

A.3.3 Subroutine PMOVE

This subroutine computes the displacement of the points describing the slice being moved. Input is the coordinates of the points, the wind components computed using subroutine WIND at the points, the fall velocity of the particles (VF), and the time interval DT.

The output of this routine is a new set of coordinates describing the slice after time step DT, which are input to the following subroutines: ACCRCY, AREA, and DPOSIT.

A.3.4 Subroutine ACCRCY

The purpose of this routine is to check the separation of two adjacent points in both the x and z directions. It is desired that two consecutive points remain less than the specified distances XC and YC apart in the x and z directions respectively. If these distances are exceeded, the subroutine PMOVE will be repeated using DT = 1/2(DT). This iteration will be done no more than three times. If after three iterations there are some points still too widely spaced, then the last results will be printed-out and the computations for that particular

fall speed will be terminated. The XC and YC values are card inputs. Output from this routine will occur only if the separations remain too large after the third iteration. The separation between consecutive points K and K + 1 is given by:

for $K = 1, \ldots, (KMX - 1)$

$$DX(K) = ABSF\,[XPN\,(K + 1) - XPN(K)]$$

$$DY(K) = ABSF\,[XPN\,(K + 1) - YPN(K)]$$

for $K = KMX$

$$DX(KMX) = ABSF\,[XPN(KMX) - XPN(1)]$$

$$DY(KMX) = ABSF\,[XPN(KMX) - YPN(1)]$$

XC and YC will be input in the present program, but subsequently will be computed for input to this subprogram.

If the accuracy criteria above are satisfied, set

$$XP(K) = XPN(K)$$

$$YP(K) = YPN(K)$$

for $K = 1, \ldots, KMX$,

and set $T = T + DT$ in which DT is the value used in the PMOVE program.

A.3.5 Subroutine AREA

The purpose of this subroutine is to compute the area of the slice and the density of the material contained within the slice after each time step. Input to this routine is the coordinates of the points after each time step and the mass of material contained within the slice. Output is density which is required as input into Subroutine DPOSIT.

Compute:

$$K = 1, \ldots, (KMX - 1)$$

$$A(K) = 1/2 * [XP(K + 1) - XP(K)] * [YP(K + 1) + YP(K)]$$

$$K = KMX$$

$$A(KMX) = 1/2 * [XP(1) - XP(KMX)] * [YP(KMX) + YP(1)].$$

Then

$$AREA = - \sum_{K=1}^{KMX} A(K).$$

We then recompute the density

DEN = XMASS/AREA.

Note: at the beginning of the main program set XMASS = TØTMAS

A.3.6 Subprogram DPOSIT

This subprogram computes the amount, if any, of the fallout during the time interval, DT, assigns it to the x-coordinate axis, and recomputes the area of the cloud above the ground together with the modified mass within the cloud.

The first step in the program is to check the Y coordinates of the KMX points. If none of these is less than zero, one may exit from the program because no deposition has occurred.

Otherwise, we compute as follows:

* Let K = 1, ..., (KMX - 1)

If YP(K) < 0, go to A,

YP(K) ≥ 0, go to B.

A. If YP(K + 1) > 0, go to 2

YP(K + 1) = 0, go to 1

YP(K + 1) < 0, go to 1

1. Area = -0.5 * [XP(K + 1) - XP(K)] * [YP(K + 1) + YP(K)]

Dep. = Den. * Area [assign to interval: XP(K) to XP(K + 1) and printout]

XMASS = XMASS - Dep.

XPN(K) = XP(K)

YPN(K) = 0

GØ TØ *

2. Compute $X = \dfrac{YP(K + 1) * XP(K) - XP(K + 1)\ YP(K)}{YP(K + 1) - YP(K)}$

Area = -0.5 * [X - XP(K)] * YP(K)

Dep. = Den. * Area [assign to interval SP(K) to X and printout]

XMASS = XMASS - Dep.

XPN(K) = XP(K)

XPN(K) = 0

GØ TØ *

B. If YP(K + 1) > 0, go to 1

YP(K + 1) = 0, go to 2

YP(K + 1) < 0, go to 3

1 and 2 . No deposition

Set DEP(K) = 0

XPN(K) = XP(K)

YPN(K) = YP(K)

GØ TØ *

3. Compute $X = \dfrac{YP(K+1) * XP(K) - XP(K+1)\ YP(K)}{YP(K+1) - YP(K)}$

Area = -0.5 * [XP(K + 1) - X] * YP(K + 1)

Dep. = Den. * Area [assign to interval X to XP(K + 1) and printout]

XMASS = XMASS - Dep.

Set XPN(K) = XP(K)

YPN(K) = YP(K)

GØ TØ *

For K = KMX, use the same procedure as above but replace (K + 1) index by 1.

A.4.0 OUTPUT

The input data is printed out, together with sufficient comments to identify the run. The final output of the run will be a tabulation of deposition, with its assigned intervals for a given slice and fall velocity.

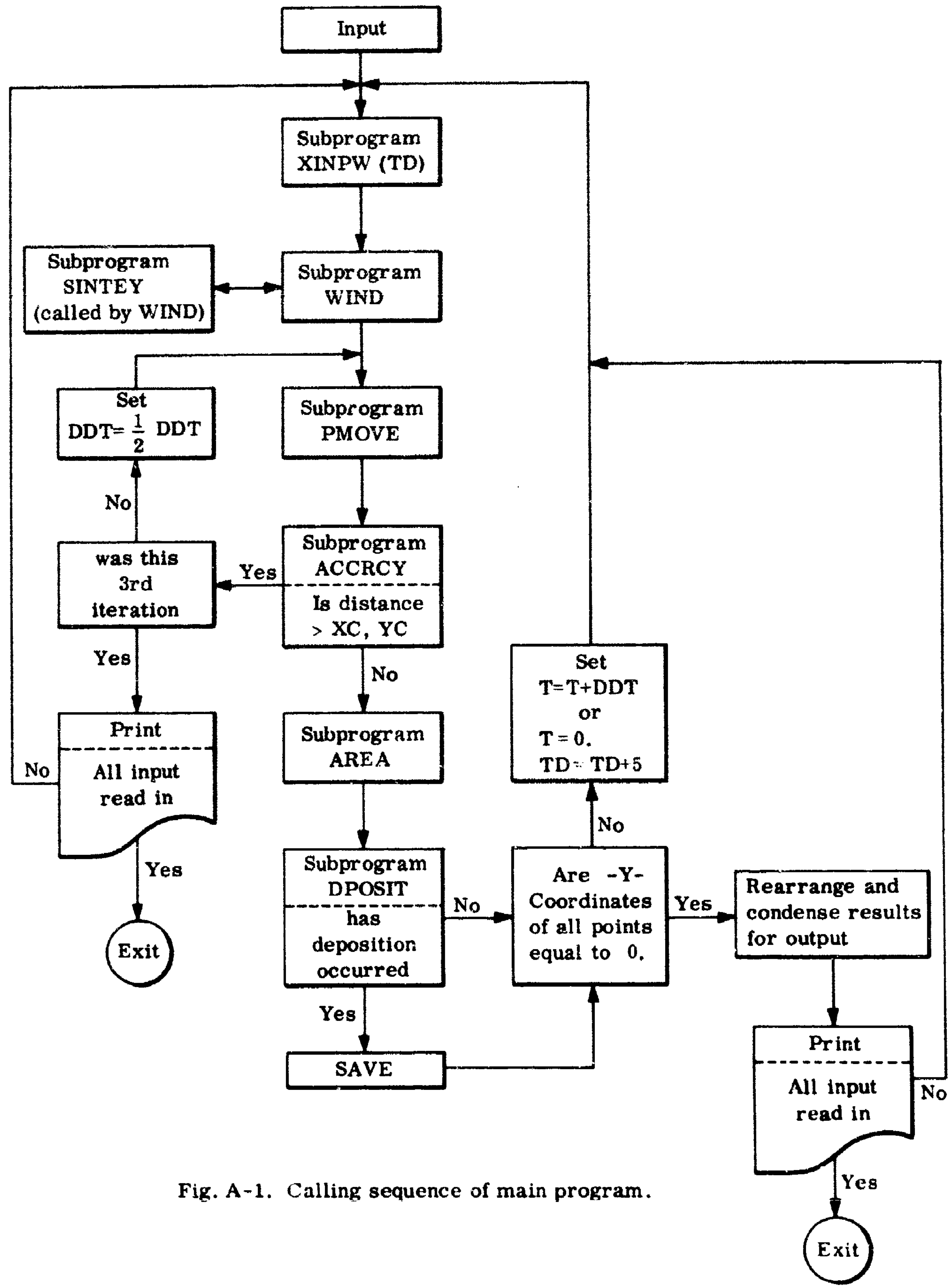


Fig. A-1. Calling sequence of main program.

APPENDIX B

FORTRAN II LISTING FOR IBM 7090/94 FALLOUT MAIN PROGRAM

THE FOLLOWING IS A FORTRAN II LISTING FOR IBM 7090/94 FALL-OUT

MAIN PROGRAM - FALL-OUT 1965

```
      DIMENSION A1(1500),B1(1500),DE1(1500),C1(1500),D1(1500),E1(1500)
      DIMENSION XP(300),YP(300),XPN(300),YPN(300),U(300),V(300)
      DIMENSION DX(300),DY(300),AR(300),DEP(300),X(300),H(3)
      COMMON XP,YP,XPN,YPN,U,V,DX,DY,AR,DEN,KMX,KM1,K,UP
      COMMON XMASS,TOTMAS,T,DT,N,VF,G,EY,DDT
      COMMON YH,YM,YT,YF,XB,S,A,YB,SB,X,H,XC,YC,DEP
      READ 333,G,A,XC,YC
      PRINT 332
      PRINT 333,G,A,XC,YC
  999 READ 222,LTS,TD,MORE,VF
      PRINT 221
  221 FORMAT(30H1   INPUT VALUES LTS,TD,MORE,VF)
      PRINT 222,LTS,TD,MORE,VF
  222 FORMAT(I4,F7.2,I3,E12.2)
      READ 444,M,(XP(K),K=1,M)
      PRINT 443
      PRINT 444,M,(XP(K),K=1,M)
      READ 444, M,(YP(K),K=1,M)
      PRINT 445
      PRINT 444,M,(YP(K),K=1,M)
      READ 555, TOTMAS,DT,YH,YF,KMX
      PRINT 554
      PRINT 555,TOTMAS,DT,YH,YF,KMX
      DO900KA=1,1500
      A1(KA)=0.
      B1(KA)=0.
      DE1(KA)=0.
  900 CONTINUE
      KDNUM=0
      MA=KMX
      MT=MA
      KM1=KMX-1
      XMASS=TOTMAS
      NT=0
      T=0.
    2 NT=NT+1
    4 IF(NT-LTS)5,5,160
    5 CALL XINPW(TD)
    6 CALL WIND
    7 N=0
      DDT=2.*DT
    8 DDT=.5*DDT
      CALL PMOVE
      CALL ACCRCY
      IF(N-1)70,8,9
    9 IF(N-3)8,266,266
  266 PRINT 500,T,NT,TD
      DO268K=1,KMX,3
  268 PRINT 501,XPN(K),YPN(K),XPN(K+1),YPN(K+1),XPN(K+2),YPN(K+2)
      IF(MORE-1)160,999,999
   70 KT=T+DDT
      CALL AREA
      DO100K=1,KMX
      IF(YP(K))105,100,100
  100 CONTINUE
      GO TO 130
  105 DO103K=1,KMX
      DEP(K)=0.
  103 X(K)=0.
```

```
      CALL UPOSIT
      DO109K=1,KMX
      XP(K)=XPN(K)
  109 YP(K)=YPN(K)
      XP(KMX+1)=XP(1)
      YP(KMX+1)=YP(1)
      NK=0
      KDNUM=KDNUM+1
      DO646K=1,KMX
      IF(DEP(K))654,646,654
  654 IF(KDNUM-1)656,656,657
  657 IF(A1( K)-XP(K))653,655,653
  655 IF(B1(K)-XP(K+1))653,659,653
  653 IF(A1(K))658,656,658
  658 NK=NK+1
      MT=MA+NK
      A1(MT)=XP(K)
      B1(MT)=XP(K+1)
      DE1(MT)=DE1(MT)+DEP(K)/ABSF(XP(K)-XP(K+1))
      GO TO 646
  656 A1( K)=XP(K)
      B1( K)=XP(K+1)
  659 DE1(K)=DE1( K)+DEP(K)/ABSF(XP(K)-XP(K+1))
  646 CONTINUE
      MA=MT
      IF(MT-1500)130,160,160
  130 DO140K=1,KMX
      IF(YP (K))150,140,150
  150 T=T+DDT
      IF(T-1800.)2,151,151
  151 TD=TD+.5
      T=0.
      IF(TD-20.)2,2,160
  140 CONTINUE
      DO675K=1,MT
      IF(A1(K)-B1(K))675,675,677
  677 A1A=A1(K)
      B1B=B1(K)
      A1(K)=B1B
      B1(K)=A1A
  675 CONTINUE
      M=2
  703 ZMAX=A1(M-1)
      ZMAX1=B1(M-1)
      ZMAX3=DE1(M-1)
      DO701I=M,MT
      IF(ZMAX-A1(I))701,701,702
  702 ZMAX=A1(I)
      ZMAX1=B1(I)
      ZMAX3=DE1(I)
      K1=I
  701 CONTINUE
      SAVA1=A1(M-1)
      SAVB1=B1(M-1)
      SAVDE1=DE1(M-1)
      A1(M-1)=ZMAX
      B1(M-1)=ZMAX1
      DE1(M-1)=ZMAX3
      A1(K1)=SAVA1
      B1(K1)=SAVB1
      DE1(K1)=SAVDE1
```

```
      M=M+1
      IF(M-MT)703,703,704
  704 C1(1)=A1(1)
      D1(1)=B1(1)
      E1(1)=DE1(1)
      II=1
      JJ=2
      MM=2
      LL=2
  715 IF(A1(JJ)-B1(II))711,711,712
  712 C1(LL)=B1(II)
      D1(LL)=A1(JJ)
      E1(LL)=0.
      C1(LL+1)=A1(JJ)
      D1(LL+1)=B1(JJ)
      E1(LL+1)=DE1(JJ)
      LL=LL+1
      GO TO 706
  711 C1(LL)=A1(JJ)
      D1(LL)=B1(JJ)
      E1(LL)=DE1(JJ)
  706 II=II+1
      JJ=JJ+1
      LL=LL+1
      IF(MM-MT)713,714,714
  713 MM=MM+1
      GO TO 715
  714 LMX=LL-1
      LMX2=LL-2
      DO800I=1,LMX2
      IF(C1(I+1)-C1(I))801,802,803
  802 A1(I)=C1(I)
      B1(I)=C1(I+1)
      DE1(I)=0.
  801 GO TO 800
  803 DE1(I)=0.
      A1(I)=C1(I)
      B1(I)=C1(I+1)
      DO804KK=1,I
      IF(D1(KK)-C1(I+1))806,805,805
  805 DE1(I)=DE1(I)+E1(KK)*(C1(I+1)-C1(I))
      GO TO 804
  806 IF(D1(KK)-C1(I))807,807,808
  807 DE1(I)=DE1(I)
      GO TO 804
  808 DE1(I)=DE1(I)+E1(KK)*(D1(KK)-C1(I))
  804 CONTINUE
  800 CONTINUE
      A1(LMX)=C1(LMX)
      B1(LMX)=D1(LMX)
      DE1(LMX)=E1(LMX)*(D1(LMX)-C1(LMX))
      DO810ME=1,LMX2
      IF(D1(ME)-C1(LMX))810,810,811
  811 DE1(LMX)=DE1(LMX)+E1(ME)*(D1(ME)-C1(LMX))
  810 CONTINUE
      PRINT 600,KT,TD,NT
      PRINT 620,VF
      DO925K=1,LMX
  925 PRINT 630,K,DE1(K),A1(K),B1(K)
      IF(MORE-1)160,999,999
  332 FORMAT(46H THE FOLLOWING DATA ARE INPUT VALUES G,A,XC,YC)
```

```
333 FORMAT(4E12.2)
444 FORMAT(I3/(6E12.2))
443 FORMAT(40H  THE FOLLOWING DATA ARE-XP-INPUT VALUES)
445 FORMAT(40H  THE FOLLOWING DATA ARE-YP-INPUT VALUES)
500 FORMAT(55H1 THIRD ITERATION REACHED, ACCURACY GREATER THAN XC,YC
   123H TIME       IN SECONDS =,F8.0/4X,3HXPN,9X,3HYPN,9X,3HXPN,9X,3HY
   2N,9X,3HXPN,9X,3HYPN/17H NUMBER OF PASS =,I4/13H HOUR OF DAY=,F7.2
501 FORMAT(6E12.5)
554 FORMAT(59H THE FOLLOWING DATA ARE INPUT VALUES TOTMAS,DT,YH,YF,
   1KMX)
555 FORMAT(4E12.2,I3)
600 FORMAT(1H1,3X,16HTIME IN SECONDS=,I6/13H HOUR OF DAY=,F7.2/13H PA
   1S NUMBER=,I4)
601 FORMAT(I3,7E12.5)
620 FORMAT(//48H   SUMMATION OF DEPOSIT WITH ITS PROPER INTERVAL/3H V
   1,E12.2/4H   K,8X,7HDEPOSIT,14X,2HA1,16X,2HB1)
630 FORMAT(I4,3E18.8)
160 CALL EXIT
    END
```

```
      SUBROUTINE XINPW(TD)
      DIMENSION XP(300),YP(300),XPN(300),YPN(300),U(300),V(300)
      DIMENSION DX(300),DY(300),AR(300),DEP(300),X(300),H(3)
      COMMON XP,YP,XPN,YPN,U,V,DX,DY,AR,DEN,KMX,KM1,K,UP
      COMMON XMASS,TOTMAS,T,DT,N,VF,C,EY,DDT
      COMMON YH,YM,YT,YF,XB,S,A,YB,DB,X,H,XC,YC,DEP
      IF(TD-10.)158,132,132
  132 TDS=TD**2
      S=((-.68*TDS)+20.4*TD-106.)*1.0E5
      UP=((-.143*TDS)+4.086*TD-22.571))*1.0E4
      IF(TD-12.)155,134,134
  134 IF(TD-18.)156,156,135
  135 IF(TD-20.)157,157,158
  155 XB=0.0
      YM=(.4)*1.0E5
      YT=(.4*TD-4.)*1.0E5
      GO TO 158
  156 XB=(-1.33*TDS+40.0*TD-288.)*1.0E5
      YM=(.4)*1.0E5
      YT=(-.044*TDS+1.33*TD-8.8)*1.0E5
      GO TO 158
  157 XB= 0.0
      YM=(.4)*1.0E5
      YT=(-.4*TD+8.)*1.0E5
  158 RETURN
      END
```

```
      SUBROUTINE WIND
      DIMENSION XP(300),YP(300),XPN(300),YPN(300),U(300),V(300)
      DIMENSION DX(300),DY(300),AR(300),DEP(300),X(300),H(3)
      COMMON XP,YP,XPN,YPN,U,V,DX,DY,AR,DEN,KMX,KM1,K,UP
      COMMON XMASS,TOTMAS,T,DT,N,VF,G,EY,DDT
      COMMON YH,YM,YT,YF,XB,S,A,YB,SB,X,H,XC,YC,DEP
      PI=3.1415927
      SB=(YF-YT)/4.
      YB=(YF+YT)/2.
      DO 40 K=1,KMX
      AYPK=A*YP(K)
      B1=1./EXPF(AYPK)
      B2=COSF(AYPK)
      IF(YP(K)-YH)20,20,13
   13 P1=(XP(K)-XB)**2
      P2=2.*S**2
      PHI=1./EXPF(P1/P2)
      H1=PHI*UP
      YTM=YT-YM
      H2=3.*YTM**2
      HD=H1/H2
      XD=(XP(K)-XB)/S**2
      YMH=YM-YH
      VM=XD*H1*YMH/2.
      VT=VM-XD*(-YTM**3 ) *HD
      XN1=YMH/2.+YTM/3.
      XN=H1*XN1
      UBAR=G*(1.-B1*B2)
      GO TO 23
   20 UHAT=0.
      UBAR=G*(1.-B1*B2)
      V(K)=0.
      U(K)=UBAR
      GO TO 40
   23 IF(YP(K)-YM)25,25,30
   25 UHAT=H1*(YP(K)-YH)/YMH
      V(K)=XD*H1*((YP(K)-YH)**2 )/(2.*YMH)
      U(K)=UBAR+UHAT
      GO TO 40
   30 IF(YP(K)-YT)33,33,35
   33 UHAT=H1*((YT-YP(K))**2 )/(YTM**2 )
      YTKM=(YT-YP(K))**3  -YTM**3
      V(K)=VM-XD*HD*YTKM
      U(K)=UBAR+UHAT
      GO TO 40
   35 IF(YP(K)-YF)38,38,44
   44 V(K)=0.
      U(K)=G*(1.-B1*B2)
      GO TO 40
   38 YKBS=(YP(K)-YB)**2
      TSBS=2.*(SB**2 )
      XF1=SQRTF(2.*PI)*SB
      XF2=1./XF1
      XF=XF2*(1./EXPF(YKBS/TSBS))
      UHAT=XN*XF
      CALL SINTEY
      V(K)=VT-(XN/XF1)*EY*XD
      U(K)=UBAR+UHAT
   40 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE SINTEY
      DIMENSION XP(300),YP(300),XPN(300),YPN(300),U(300),V(300)
      DIMENSION DX(300),DY(300),AR(300),DEP(300),X(300),H(3)
      COMMON XP,YP,XPN,YPN,U,V,DX,DY,AR,DEN,KMX,KM1,K,UP
      COMMON XMASS,TOTMAS,T,DT,N,VF,G,EY,DDT
      COMMON YH,YM,YT,YF,XB,S,A,YB,SB,X,H,XC,YC,DEP
      SINK= 32.
      YEE=YT
      INK=SINK/2.
      ZINK=(YP(K)-YT)/SINK
      SUM=0.
      R=0.
      CON=2.*(SB*SB)
      DO 15I=1,INK
      DO 16J=1,3
      TEMP=(((YEE+R)-YB)**2 )/CON
      H(J)=1./EXPF(TEMP)
   16 R=R+ZINK
      R=0.
      SUM=SUM+(ZINK/3.)*(H(1)+4.*H(2)+H(3))
   15 YEE=YEE+2.*ZINK
      EY=SUM
      RETURN
      END
```

```
      SUBROUTINE PMOVE
      DIMENSION XP(300),YP(300),XPN(300),YPN(300),U(300),V(300)
      DIMENSION DX(300),DY(300),AR(300),DEP(300),X(300),H(3)
      COMMON XP,YP,XPN,YPN,U,V,DX,DY,AR,DEN,KMX,KM1,K,UP
      COMMON XMASS,TOTMAS,T,DT,N,VF,G,EY,DDT
      COMMON YH,YM,YT,YF,XB,S,A,YB,SB,X,H,XC,YC,DEP
      DO 42K=1,KMX
      FKT=-(V(K)+VF)*DDT
      IF(YP(K)-FKT)38,36,36
   36 XPN(K)=XP(K)+U(K)*DDT
      YPN(K)=YP(K)+(V(K)+VF)*DDT
      GO TO 42
   38 DTP=-YP(K)/(V(K)+VF)
      TAU=DDT-DTP
      XPN(K)=XP(K)+U(K)*DTP
      YPN(K)=VF*TAU
   42 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE ACCRCY
      DIMENSION XP(300),YP(300),XPN(300),YPN(300),U(300),V(300)
      DIMENSION DX(300),DY(300),AR(300),DEP(300),X(300),H(3)
      COMMON XP,YP,XPN,YPN,U,V,DX,DY,AR,DEN,KMX,KM1,K,UP
      COMMON XMASS,TOTMAS,T,DT,N,VF,G,EY,DDT
      COMMON YH,YM,YT,YF,XB,S,A,YB,SB,X,H,XC,YC,DEP
      DO 48K=1,KM1
      DX(K)=ABSF(XPN(K+1)-XPN(K))
      IF(XC-DX(K))62,62,46
   46 DY(K)=ABSF(YPN(K+1)-YPN(K))
      IF(YC-DY(K))62,62,48
   48 CONTINUE
      DX(KMX)=ABSF(XPN(KMX)-XPN(1))
      IF(XC-DX(KMX))62,62,50
   50 DY(KMX)=ABSF(YPN(KMX)-YPN(1))
      IF(YC-DY(KMX))62,62,54
   62 N=N+1
      RETURN
   54 CONTINUE
      N=0
      DO 55K=1,KMX
      XP(K)=XPN(K)
   55 YP(K)=YPN(K)
      RETURN
      END
```

```
      SUBROUTINE AREA
      DIMENSION XP(300),YP(300),XPN(300),YPN(300),U(300),V(300)
      DIMENSION DX(300),DY(300),AR(300),DEP(300),X(300),H(3)
      COMMON XP,YP,XPN,YPN,U,V,DX,DY,AR,DEN,KMX,KM1,K,UP
      COMMON XMASS,TOTMAS,T,DT,N,VF,G,EY,DDT
      COMMON YH,YM,YT,YF,XB,S,A,YB,SB,X,H,XC,YC,DEP
      DO 75K=1,KM1
      DXP=XP(K+1)-XP(K)
      DYP=YP(K+1)+YP(K)
   75 AR(K)=.5*DXP*DYP
      DMXP=XP(1)-XP(KMX)
      DMYP=YP(KMX)+YP(1)
      AR(KMX)=.5*DMXP*DMYP
      AREA=0.
      DO 76K=1,KMX
   76 AREA=AREA+AR(K)
      DEN=XMASS/(-AREA)
      RETURN
      END
```

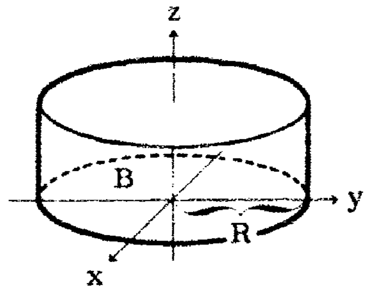
```
      SUBROUTINE DPOSIT
      DIMENSION XP(300),YP(300),XPN(300),YPN(300),U(300),V(300)
      DIMENSION DX(300),DY(300),AR(300),DEP(300),X(300),H(3)
      COMMON XP,YP,XPN,YPN,U,V,DX,DY,AR,DEN,KMX,KM1,K,DP
      COMMON XMASS,TOTMAS,T,DT,N,VF,G,EY,DDT
      COMMON YH,YM,YT,YF,XB,S,A,YB,SB,X,H,XC,YC,DEP
      XP(KMX+1)=XP(1)
      YP(KMX+1)=YP(1)
      DO125K=1,KMX
      KK=K+1
  108 IF(YP(K))110,115,115
  110 IF(YP(KK))111,111,112
  111 ARE1=-.5*(XP(KK)-XP(K))*(YP(KK)+YP(K))
      DEP(K)=DEN*ARE1
      XMASS=XMASS-DEP(K)
      XPN(K)=XP(K)
      YPN(K)=0.
      GO TO 125
  112 YXXY=YP(KK)*XP(K)-XP(KK)*YP(K)
      X(K)=YXXY/(YP(KK)-YP(K))
      ARE1=-.5*(X(K)-XP(K))*YP(K)
      DEP(K)=DEN*ARE1
      XMASS=XMASS-DEP(K)
      XPN(K)=XP(K)
      YPN(K)=0.
      GO TO 125
  115 IF (YP(KK))120,118,118
  118 DEP(K)=0.
      XPN(K)=XP(K)
      YPN(K)=YP(K)
      GO TO 125
  120 YXXY=YP(KK)*XP(K)-XP(KK)*YP(K)
      X(K)=YXXY/(YP(KK)-YP(K))
      ARE1=-.5*(XP(KK)-X(K))*YP(KK)
      DEP(K)=DEN*ARE1
      XMASS=XMASS-DEP(K)
      XPN(K)=XP(K)
      YPN(K)=YP(K)
  125 CONTINUE
      RETURN
      END
```

APPENDIX C

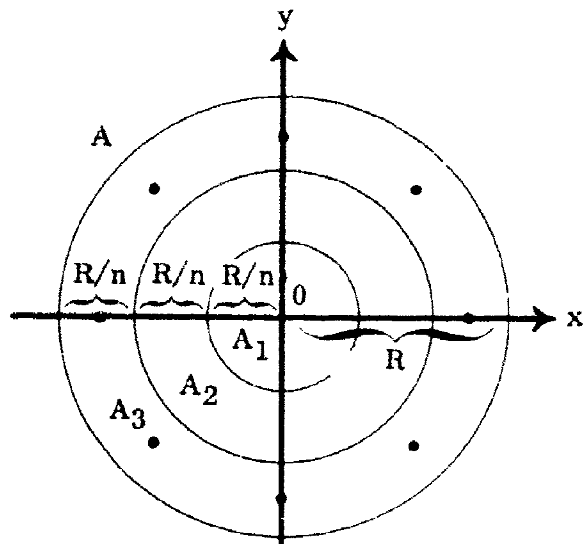
THREE-DIMENSIONAL FALLOUT COMPUTATION SCHEME

The stem and cloud is originally subdivided into discs and further subdivided into wafers. As was stated in the text of this report, when the center of the wafer reaches an altitude below which local circulations are permitted, we further subdivide the wafer into smaller volume elements. Presented below is the method by which this further subdivision is achieved.

Given a cylinder $C = BXI$ where B is a disc of radius R, and $I = (0, d)$,



C is to be partitioned into equal volume elements each of which has a "center of concentration" whose coordinates are to be determined. The partitioning is to be done by taking $m + 1$ cross-sections at right angles to the z-axis to give m layers of height d/m, and then by distributing the centers of the volume elements in each layer as follows.



If we take concentric circles of radius $(R/n)j$, $j = 1, \ldots, n$, we can decompose any cross-section, A, into the sum of n annuli, $A_1, \ldots, A_n$ (the center degenerate annulus A_1 being the (R/n)-disc). The area of the jth annulus is given by

$$\text{Area}(A_j) = \pi\left(\frac{R}{n}j\right)^2 - \pi\left[\frac{R}{n}(j-1)\right]^2$$

$$= \pi\left(\frac{R}{n}\right)^2 (j^2 - j^2 + 2j - 1)$$

$$= \pi\left(\frac{R}{n}\right)^2 (2j - 1)$$

Note that $\sum_{j=1}^{n} \text{Area}(A_j) = \pi\left(\frac{R}{n}\right)^2 \sum_{j=1}^{n} (2j-1) = \pi\left(\frac{R}{n}\right)^2 (1 + 3 + \ldots + 2n-1)$

$= \pi\left(\frac{R}{n}\right)^2 \frac{n}{2}(2n) = \pi R^2$, the total cross-sectional area, Area (A).

Then

$$\frac{\text{Area}(A_j)}{\text{Area}(A)} = \frac{\pi\left(\frac{R}{n}\right)^2 (2j-1)}{\pi R^2} = \frac{2j-1}{n^2} < 1$$

gives the fraction of the total area taken up by A_j.

If in each layer there are required to be N centers of elemental volume it would be desirable to have $[(2j - 1)/n^2] \cdot N$ center points in the jth annulus A_j, $j = 1, \ldots, n$.

Then

$$N_j = \left[\frac{2j-1}{n^2}\right] N$$

must be an integer for each j. Then N/n^2 must be an integer, or $N = Kn^2$ for K an integer. So given the overall number of points N, we must find suitable K and n such that the preceding relation holds.

In each A_j, $j \neq 1$, it is desirable to distribute the N_j "center" points on the mid-circle of the annulus at equal distances apart. These mid-circles have radii $(R/n)(j - 1/2)$, $j = 2, \ldots, n$. In the jth annulus, the N_j points are $2\pi/N_j$ radians apart. If one point is located on the x-axis (so that $\Theta = 0$) in polar coordinates, the "center points" in A_j are at

$$(\rho, \Theta) = \left[\frac{R}{n}(j - 1/2),\ p\frac{2\pi}{N_j}\right], \qquad \begin{array}{l} p = 0, 1, \ldots, N_j - 1 \\ j = 1, 2, \ldots, n. \end{array}$$

For $j = 1$ (the center disc), we put one point at the origin (0, 0) and the remaining $N_1 - 1$ points at

$$\left[\frac{R}{2n}, \; p\frac{2\pi}{N_1 - 1} \right], \qquad p = 0, 1, \ldots, N_1 - 2,$$

so that they lie on the circle of radius $1/2\,(R/n)$.